Solution to the $B \to \pi K$ Puzzle in a Flavor Changing Z' Model

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based on work with V. Barger, C.W. Chiang and P. Langacker

- $B \to \pi K$ Puzzle
- Necessary EWP Enhancement
- Flavor-changing Z' Model
- Z' Solution of $B \to \pi K$ Puzzle
- Implications of the Solution
- Conclusion

$B \to \pi K$ **Puzzle**

It is an anomaly in $B \to \pi K$ Branching Ratios.

BaBar, Belle and CLEO average:

$$
\begin{aligned}
R_{\rm c} &\equiv 2\left[\frac{\mathrm{BR}(B^+ \to \pi^0 K^+) + \mathrm{BR}(B^- \to \pi^0 K^-)}{\mathrm{BR}(B^+ \to \pi^+ K^0) + \mathrm{BR}(B^- \to \pi^- \overline{K^0})}\right] \\
&= 1.15 \pm 0.12 \ \gtrsim \ (\text{SM prediction})
\end{aligned}
$$

$$
\begin{aligned}
R_{\rm n} &\equiv \frac{1}{2}\left[\frac{\mathrm{BR}(B^0 \to \pi^- K^+) + \mathrm{BR}(\overline{B^0} \to \pi^+ K^-)}{\mathrm{BR}(B^0 \to \pi^0 K^0) + \mathrm{BR}(\overline{B^0} \to \pi^0 \overline{K^0})}\right] \\
&= 0.78 \pm 0.10 \ < \ (\text{SM prediction})
\end{aligned}
$$

In SM, $R_{\rm c} \approx R_{\rm n}$ (with value ≈ 1.1), but experimental data shows there is a 2.4σ difference.
$R_{\rm c} > 1$ and $R_{\rm n} < 1$ is a consistent pattern by separate BaBar, Belle and CLEO data.

The $B^\pm \to \pi^0 K^\pm$ and $B^0 \to \pi^0 K^0$ has color-allowed EWP(EW Penguin) contribution. NP(New Physics) which enhances the EWP may explain $B \to \pi K$ data.

$B \to \pi K$ Decay Modes

$$\begin{aligned}
A(B^+ \to \pi^+ K^0) &= -P' \\
\sqrt{2}A(B^+ \to \pi^0 K^+) &= P'\left[1 - \left(e^{i\gamma} - qe^{i\varphi}\right) r_c e^{i\delta_c}\right] \\
A(B_d^0 \to \pi^- K^+) &= P'\left[1 - re^{i\delta}e^{i\gamma}\right] \\
\sqrt{2}A(B_d^0 \to \pi^0 K^0) &= -P'\left[1 + \rho_n e^{i\theta_n}e^{i\gamma} - qe^{i\varphi} r_c e^{i\delta_c}\right] \\
\text{with} \quad & P' \equiv A\lambda^2(\mathcal{P}'_t - \mathcal{P}'_c)
\end{aligned}$$

We follow Buras et al.'s approach:

[PRL92, 101804 (2004)]

1. Assume no manifest NP effect in (QCD penguin sensitive) $B \to \pi\pi$. (Though $B \to \pi\pi$ data shows its own puzzling pattern, there are indications it is due to non-factorizable effect rather than NP.)
2. Assume $SU(3)$ flavor symmetry.
3. Then $B \to \pi\pi$ ($\Delta S = 0$) data provide the $B \to \pi K$ ($|\Delta S| = 1$) hadronic parameters except EWP parameters (q and φ). ($B \to \pi\pi$ is not sensitive to EWP.)

$$\begin{aligned}
r &= 0.11^{+0.07}_{-0.05} & \delta &= +(42^{+23}_{-19})^\circ \\
\rho_n &= 0.13^{+0.07}_{-0.05} & \theta_n &= -(29^{+21}_{-26})^\circ \\
r_c &= 0.20^{+0.09}_{-0.07} & \delta_c &= +(2^{+23}_{-18})^\circ
\end{aligned}$$

Only EWP sector is assumed to have a manifest NP effect.

Necessary EWP Enhancement

$B \to \pi K$ EWP sector are parametrized by q and φ.

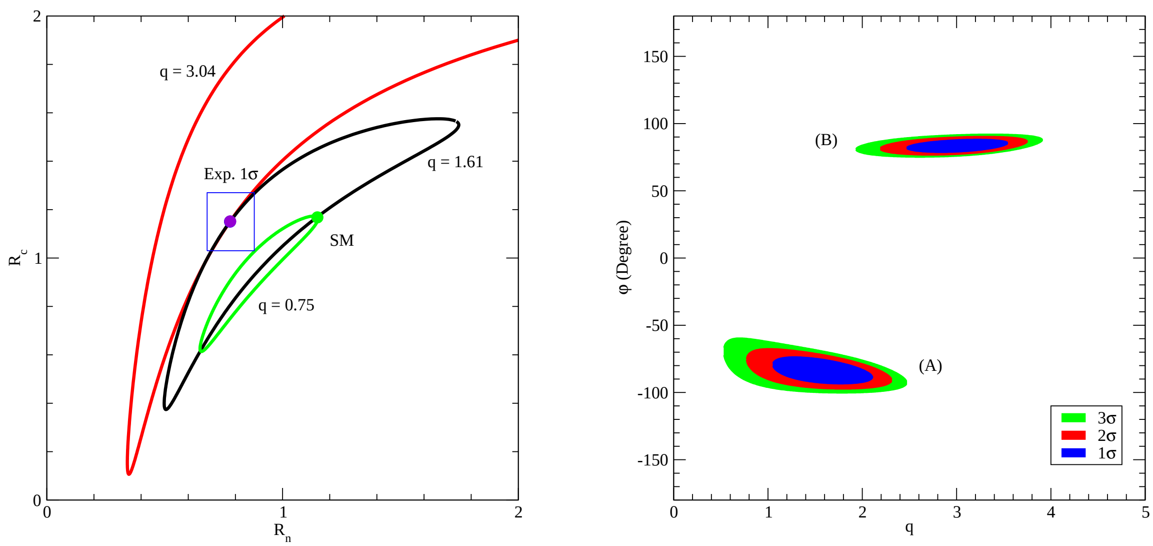
$$
\begin{aligned}
qe^{i\varphi} &\equiv \frac{P'_{\text{EW}}}{T' + C'} \\
&\simeq -\frac{3}{2}\frac{1}{\lambda|V_{ub}/V_{cb}|}\left[\frac{c_9(m_b) + c_{10}(m_b)}{c_1(m_b)\tilde{\xi} + c_2(m_b)}\right]
\end{aligned}
$$

with

$$
\tilde{\xi} \equiv \frac{\sqrt{2}\langle K^0\pi^0|O_1^{(u)}|B^0\rangle + \langle K^+\pi^-|O_1^{(u)}|B^0\rangle}{\sqrt{2}\langle K^0\pi^0|O_2^{(u)}|B^0\rangle + \langle K^+\pi^-|O_2^{(u)}|B^0\rangle}
$$

$\tilde{\xi} = 1$ in our $SU(3)$ flavor symmetry limit. Then SM prediction of EWP parameters are

$$
\{q, \varphi\}|_{SM} = \{0.75, 0^\circ\}.
$$



[Two-fold solutions of enhanced EW penguin that satisfy R_n and R_c]

Two-fold solutions are found to satisfy $B \to \pi K$ data, R_n and R_c (with only central values of the hadronic parameters obtained from $B \to \pi\pi$).

$$\begin{aligned}\text{(A) } \{q, \varphi\} &= \{1.61, -84^\circ\} \\ \text{(B) } \{q, \varphi\} &= \{3.04, +83^\circ\}\end{aligned}$$

We need an enhanced magnitude and new phase in EWP sector ($\{q, \varphi\}|_{SM} = \{0.75, 0^\circ\}$). Next, we will explore if the flavor-changing Z' model can provide them.

Motivation of TeV-scale $U(1)'$ Model

- Top-down:
  Extra $U(1)$'s are predicted by many types of new physics (GUT, String, Extra-dim).

- Bottom-up:
  It solves the μ-problem of MSSM in a most natural fashion.

$$\mu \widehat{H}_1 \cdot \widehat{H}_2 \rightarrow h_s \widehat{S} \widehat{H}_1 \cdot \widehat{H}_2$$
$$\mu^{\text{eff}} \equiv h_s \langle S \rangle \sim \mathcal{O}(EW)$$

  S is a singlet Higgs to break $U(1)'$ at TeV-scale. NMSSM (has S with a discrete $\mathbf{Z}_3$ symmetry) suffers from the domain wall problem.

- Near-future Experiments:
  Direct and indirect search will be available shortly - LHC direct Z' search, Precision test, Particle spectrum different from MSSM.

  Current Tevatron/LEP limit on Z':

$$\left(\begin{array}{l} M_{Z'} > (500 - 800)\text{GeV} \\ \\ \delta_{Z-Z'} < (\text{a few}) \times 10^{-3} \end{array} \right.$$

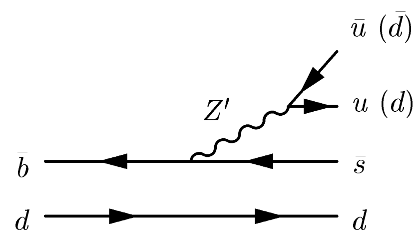
What TeV-scale $U(1)'$ Introduces

- Additional gauge boson: Z' ($\sim$ TeV-scale)
- Extra SM singlet Higgs: S (to break $U(1)'$ spontaneously)
- Their superpartners: $\tilde{Z}'$, $\tilde{S}$ (provides 6-component neutralinos with $\tilde{Z}$, $\tilde{\gamma}$, $\tilde{H}_1^0$, $\tilde{H}_2^0$ of MSSM)
- Possible flavor-changing coupling: Despite suppression by large Z' mass, tree-level FCNC may be sizable.

TeV-scale $U(1)'$ extension of MSSM can be viewed as the **minimal supersymmetric extension of SM** free from fine-tuning (μ-problem) and domain wall (NMSSM) at the cost of additional gauge symmetry and its breaking mechanism.

FCNC Mediated by Z'

Z' may have a flavor-changing coupling unlike the SM Z.



[Tree-level FCNC by Z' in $B^0 \to \pi^0 K^0$ decay mode]

For example, certain String models construct families differently. Chaudhuri et al.'s model [NPB456, 89 (1995)] can have $U(1)'$ broken at TeV-scale with 3rd generation quark coupling different from the first two families [Cleaver et al.: NPB525, 3 (1998)]. (family non-universal couplings)

Then flavor-changing couplings and possibly new CP-violating effect occur in the physical eigenstate.

(Ex) Left-handed d-type quark $U(1)'$ coupling matrix

$$
\begin{aligned}
\mathcal{L} &= -g_{Z'} Z'_\mu \left(\bar{d}_L^{\text{int}} \gamma_\mu \epsilon_{d_L} d_L^{\text{int}} \right) \\
&= -g_{Z'} Z'_\mu \left(\bar{d}_L \gamma_\mu B^L d_L \right)
\end{aligned}
$$

- $U(1)'$ coupling matrix in interaction eigenstate (d_L^{int}):

$$
\epsilon_{d_L} = Q_{d_L} \begin{array}{cc} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1+\delta \end{pmatrix} & \begin{array}{c} d \\ s \\ b \end{array} \end{array}
$$

- $U(1)'$ coupling matrix in mass eigenstate ($d_L = V_{d_L} d_L^{\text{int}}$):

$$
\begin{aligned}
B^L &\equiv V_{d_L} \epsilon_{d_L} V_{d_L}^\dagger = Q_{d_L} V_{d_L} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1+\delta \end{pmatrix} V_{d_L}^\dagger \\
&= \left[\begin{array}{ll} Q_{d_L} \mathbf{1_{3\times3}} & (\text{if } \delta = 0) \\ \\ \text{general } 3\times3 \text{ matrix} & (\text{if } \delta \neq 0) \end{array} \right.
\end{aligned}
$$

B^L has off-diagonal terms with phases originated from V_{d_L}. (And similarly for u-type quark and/or Right-handed coupling.)

The usual CKM matrix is given by $V_{CKM} = V_{u_L} V_{d_L}^\dagger$.

Simplifications in Our Analysis

We simplify our Z' model by assuming:

1. Only left-handed coupling (like SM weak interaction)

2. No RG effect between $M_{Z'}$ and M_W scale.

3. Negligible Z' effect on QCD penguin ($\Delta c_3 = 0$) so that NP is manifest only in the EWP sector.

(The most general Z' model has many undetermined parameters. Our simplifications provides a way to introduce the Z' effect minimally to explain $B \to \pi K$ data.)

$$\mathcal{H}_{\text{eff}}^{Z'} = \frac{2G_F}{\sqrt{2}} \left(\frac{g_{Z'} M_Z}{g_Z M_{Z'}} \right)^2 B_{sb}^{L*} (\bar{b}s)_{V-A} \sum_q B_{qq}^L (\bar{q}q)_{V-A} + \text{h.c.}$$

$$\begin{aligned} \text{QCD penguin}: \quad O_3^{(q)} &= (\bar{b}s)_{V-A}(\bar{q}q)_{V-A} \\ \text{EW penguin}: \quad O_9^{(q)} &= \frac{3}{2} e_q (\bar{b}s)_{V-A}(\bar{q}q)_{V-A} \end{aligned}$$

$$\begin{aligned} \Delta c_3(M_W) &= 0 \quad \text{(Negligible effect on QCD penguin)} \\ \Delta c_9(M_W) &= \frac{4}{V_{tb}^* V_{ts}} \left(\frac{g_{Z'} M_Z}{g_Z M_{Z'}} \right)^2 B_{sb}^{L*} B_{dd}^L \end{aligned}$$

Now our Z' effect can be given as an addition of Δc_9.

$$\mathcal{H}_{\text{eff}}^{Z'} = -\frac{G_F}{\sqrt{2}}(V_{tb}^* V_{ts})\Delta c_9 \sum_q O_9^{(q)} + \text{h.c.}$$

with

$$\Delta c_9(M_W) = 4\frac{|V_{tb}^* V_{ts}|}{V_{tb}^* V_{ts}}\xi^{LL} e^{-i\phi_L}$$

written in terms of 2 real independent parameters.

$$\left(\begin{array}{l} \xi^{LL} \equiv \left(\frac{g_{Z'} M_Z}{g_Z M_{Z'}}\right)^2 \left|\frac{B_{sb}^{L*} B_{dd}^L}{V_{tb}^* V_{ts}}\right| \\ \\ \phi_L \equiv \text{Arg}\left[B_{sb}^L\right] \end{array} \right)$$

[Wilson coefficients at both M_W and m_b scales]

Op.	$c_i^{SM}(M_W)$	$\Delta c_i(M_W)$	$c_i^{SM}(m_b)$	$\Delta c_i(m_b)$
$O_1^{(q)}$	0.981	0	1.138	0.0
$O_2^{(q)}$	0.053	0	-0.296	0.0
$O_3^{(q)}$	0.001	0	0.014	0.0
$O_4^{(q)}$	-0.002	0	-0.029	$-0.1\xi^{LL}e^{-i\phi_L}$
$O_5^{(q)}$	0.001	0	0.008	0.0
$O_6^{(q)}$	-0.002	0	-0.036	$-0.2\xi^{LL}e^{-i\phi_L}$
$O_7^{(q)}$	0.001	0	0.000	0.0
$O_8^{(q)}$	0	0	0.000	0.0
$O_9^{(q)}$	-0.008	$-4.0\xi^{LL}e^{-i\phi_L}$	-0.010	$-4.5\xi^{LL}e^{-i\phi_L}$
$O_{10}^{(q)}$	0	0	0.002	$+1.2\xi^{LL}e^{-i\phi_L}$

Solution of $B \to \pi K$ Puzzle in Z' Model

EWP parameters q and φ in terms of Z' parameters ξ^{LL} and ϕ_L:

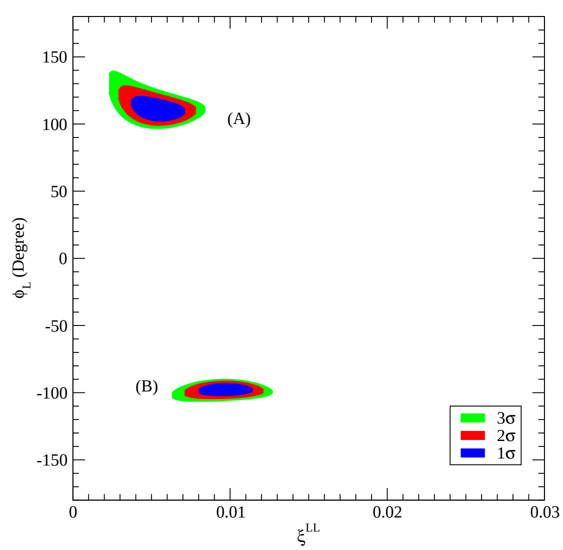
$$
\begin{aligned}
qe^{i\varphi} &\simeq -\frac{3}{2}\frac{1}{\lambda|V_{ub}/V_{cb}|}\left[\frac{c_9(m_b)+c_{10}(m_b)}{c_1(m_b)+c_2(m_b)}\right] \\
&\approx 0.75(1+410\xi^{LL}e^{-i\varphi})
\end{aligned}
$$

The Z' solutions are found to be (using the central values of the hadronic parameters)

$$
\begin{aligned}
\text{(A)}\ \{\xi^{LL},\phi_L\} &= \{0.0055, 110^\circ\} \quad \text{(for small } q) \\
\text{(B)}\ \{\xi^{LL},\phi_L\} &= \{0.0098, -97^\circ\} \quad \text{(for large } q)
\end{aligned}
$$

that correspond to earlier two-fold solutions

$$
\begin{aligned}
\text{(A)}\ \{q,\varphi\} &= \{1.61, -84^\circ\} \\
\text{(B)}\ \{q,\varphi\} &= \{3.04, +83^\circ\}
\end{aligned}
$$



[Contours of Z' solutions to $B \to \pi K$ puzzle]

Our flavor-changing Z' can provide the necessary EWP enhancement to explain $B \to \pi K$ data.

Implications on Z' Coupling and Mass

From

$$\xi^{LL} \equiv \left(\frac{g_{Z'} M_Z}{g_Z M_{Z'}}\right)^2 \left|\frac{B_{sb}^{L*} B_{dd}^L}{V_{tb}^* V_{ts}}\right|$$

$$\text{(l.h.s.)} \;=\; \mathcal{O}(0.01) \qquad \text{(from } B \to \pi K \text{ solution)}$$

$$\text{(r.h.s.)} \;=\; \mathcal{O}\left(\frac{M_Z}{M_{Z'}}\right)^2 \left|\frac{B_{sb}^{L*} B_{dd}^L}{0.04}\right| \qquad \text{(for } g_{Z'} \sim \mathcal{O}(g_Z))$$

$$M_{Z'} \sim \mathcal{O}(10\ M_Z) \quad \Longleftrightarrow \quad \left|B_{sb}^{L*} B_{dd}^L\right| \sim \mathcal{O}(0.04)$$

(TeV-scale) (natural size)

Predictions on Other EWP-sensitive $B \to \pi K$ Observables

SM predictions:

$$\begin{aligned} S_{\pi K_s}|_{SM} &= 0.86^{+0.07}_{-0.05} \\ A_{\pi K_s}|_{SM} &= -0.12^{+0.13}_{-0.11} \\ A_{CP}(\pi^0 K^\pm)|_{SM} &= -0.01^{+0.10}_{-0.14} \end{aligned}$$

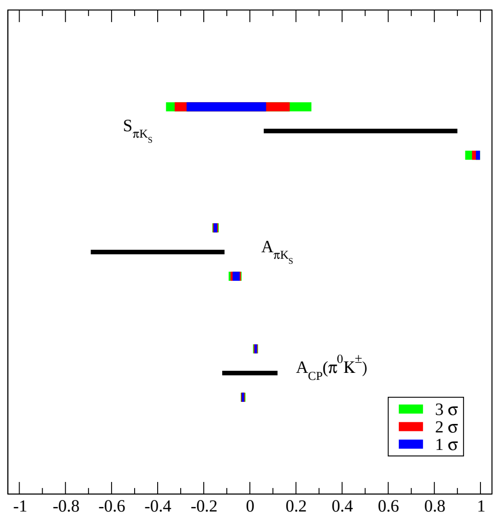
Current experimental data:

$$\begin{aligned} S_{\pi K_s}|_{EXP} &= 0.48 \pm 0.42 \text{ (BaBar first data)} \\ A_{\pi K_s}|_{EXP} &= -0.40 \pm 0.29 \text{ (BaBar first data)} \\ A_{CP}(\pi^0 K^\pm)|_{EXP} &= 0.00 \pm 0.12 \ (S = 1.79) \end{aligned}$$

Consistent with SM. But not conclusive yet.

Z' solution predictions:

(using central values of the hadronic parameters)



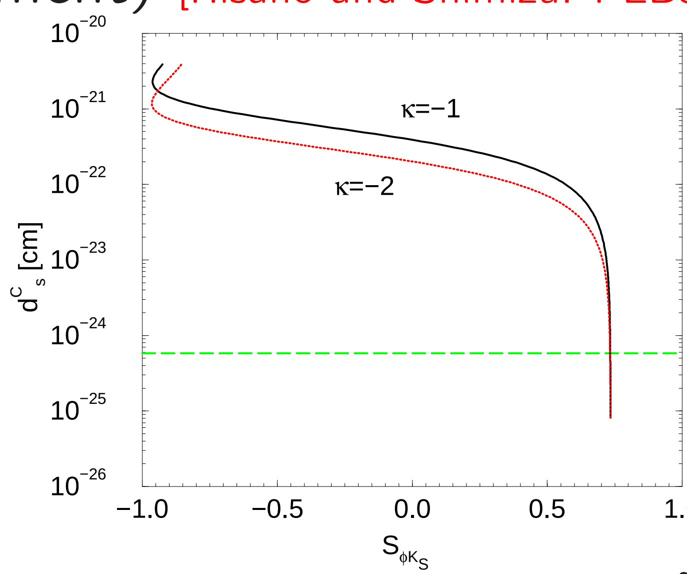
[Lower bar for solution (A), Upper bar for (B), Black bar for exp. 1σ]

While Solution (B) ($\{q, \varphi\} = \{3.04, +83^\circ\}$) is consistent with experimental data,
Solution (A) ($\{q, \varphi\} = \{1.61, -84^\circ\}$) shows slight deviations from the first BaBar 1σ range of $S_{\pi K_S}$ and $A_{\pi K_S}$. (needs future confirmation by more data)

Relation to $B \to \phi K_S$ and ^{199}Hg EDM

$B \to \phi K_S$ is a NP sensitive decay mode since SM contribution is only loop-order. $S_{\phi K_s}$ at Belle shows a 3.5σ deviation from the SM expectation (0.73 ± 0.06). (Exp average: $S_{\phi K_s} = -0.15 \pm 0.70$ ($S = 2.1$))

SUSY solutions with right-handed squark mixing may result in too large Mercury atom EDM(Electric Dipole Moment) [Hisano and Shimizu: PLB581, 224 (2004)].



[s-quark CEDM vs $S_{\phi K_S}$ correlated by $\tilde{s}_R$-$\tilde{b}_R$ mixing]

A flavor-changing Z' solution [Barger,Chiang, Langacker and Lee: PLB580, 186 (2004)] is not directly related to right-handed squark mixing or the Mercury EDM and therefore safe from its constraint.

Prediction from our $B \to \pi K$ solutions:

$$
\begin{aligned}
&(A)\ S_{\phi K_s} = 0.99 \\
&(B)\ S_{\phi K_s} = -0.69 \quad \text{(within averaged exp. } 1\sigma)
\end{aligned}
$$

Summary and Conclusions

- We reviewed the $B \to \pi K$ puzzle in a view of NP indications in EWP sector.
- TeV-scale Z' model is a well-motivated NP candidate and may have FCNC at tree-level.
- It turns out a flavor-changing Z' model can provide the magnitude and phase in EWP sector and explain $B \to \pi K$ data (even with limitations of left-handed coupling only).
- The solution suggests Z' mass of TeV-scale is consistent with natural size of couplings.
- There exists a Z' solution that can account for both πK and ϕK_S anomalies.